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Europ. J. Agronomy 22 (2005) 71–84
European Journal of Agronomy
www.elsevier.com/locate/eja

Growth and yield of winter wheat in the first 3 years of a monoculture under varying N fertilization in NW Germany

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Received 5 November 2002; received in revised form 22 December 2003; accepted 22 December 2003

Abstract

Different preceding crops interact with almost all husbandry and have a major effect on crop yields. In order to quantify the yield response of winter wheat, a field trial with different preceding crop combinations (oilseed rape (OSR)–OSR–OSR–wheat–wheat–wheat), two sowing dates (mid/end of September, mid/end of October) and 16 mineral nitrogen (N) treatments (80–320 kg N ha^{-1}) during 1993/1994–1998/1999, was carried out at Hohenschulen Experimental Station near Kiel in NW Germany. Single plant biomass, tiller numbers m^{-2}, biomass m^{-2}, grain yield and yield components at harvest were investigated. During the growing season, the incidence of root rot (*Gaeumannomyces graminis*) was observed. Additionally, a bioassay with *Lemna minor* was used to identify the presence of allelochemicals in the soil after different preceding crops.

Averaged over all years and all other treatments, wheat following OSR achieved nearly 9.5 t ha^{-1}, whereas the second wheat crop following wheat yielded about 0.9 t ha^{-1} and the third wheat crop following 2 years of wheat about 1.9 t ha^{-1} less compared with wheat after OSR. A delay of the sowing date only marginally decreased grain yield by 0.2 t ha^{-1}. Nitrogen fertilization increased grain yield after all preceding crop combinations, but at different levels. Wheat grown after OSR reached its maximum yield of 9.7 t ha^{-1} with 210 kg N ha^{-1}. The third wheat crop required a N amount of 270 kg N ha^{-1} to achieve its yield maximum of 8.0 t ha^{-1}.

Yield losses were mainly caused by a lower ear density and a reduced thousand grain weight. About 4 weeks after plant establishment, single wheat plants following OSR accumulated more biomass compared to plants grown after wheat. Plants from the third wheat crop were smallest. This range of the preceding crop combinations was similar at all sampling dates throughout the growing season.

Root rot occurred only at a low level and was excluded to cause the yield losses. The *Lemna* bioassay suggested the presence of allelochemicals, which might have been one reason for the poor single plant development in autumn.

An increased N fertilization compensated for the lower number of ears m^{-2} and partly reduced the yield losses due to the unfavorable preceding crop combination. However, it was not possible to completely compensate for the detrimental influences of an unfavorable preceding crop on the grain yield of the subsequent wheat crop.

Keywords: Winter wheat; Yield; Yield components; Preceding crop combination; *Lemna* bioassay; Root rot

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1161-0301/$ – see front matter
doi:10.1016/j.eja.2003.12.004

1. Introduction

Cereal rotations with a large proportion of winter wheat are typical of large areas of northern Europe and other humid climates. Winter wheat in monoculture is occasionally recommended as financially the most competitive 'rotation'. However, unfavorable preceding crops and continuous cropping inevitably cause yield losses. Compared with wheat grown after oilseed rape (OSR), peas or oats, yield of wheat after wheat is reduced by 8–57%, depending on the site, weather conditions and crop management (e.g. Zimmermann, 1984; Widdowson et al., 1985; Prew et al., 1986; McEwen et al., 1989; Christen, 1998). Previous research at Kiel revealed that the yield reduction was mainly due to a lower number of ears m^{-2} and a reduced thousand grain weight, whereas the number of kernels per ear showed only a small decrease or, in some cases, even compensated for a poor ear density (Christen, 1998). Thorne et al. (1988) observed that wheat plants grown after oilseed rape showed a better development in autumn compared with wheat following oats.

Yield losses might be due to different mechanisms such as exhaustion of nutrient(s), weeds (grasses), pests or diseases. In addition, negative changes in the soil structure, reduced nutrient transformation caused by a lower activity of soil micro-organisms and the release of phytotoxic substances from crop residues may occur.

The soil-borne fungus *Gaeumannomyces graminis* (causing take-all) can be regarded as the most important disease on winter wheat in rotations with high proportion of cereals. The fungus interrupts the water and nutrient transport in the roots and at the stem base. Due to its temperature adaptation, take-all normally develops poorly in autumn, but very effectively in spring and early summer, when soil temperature has increased (Wong, 1980). Under the soil and climatic conditions in NW Europe, take-all mainly reduces the thousand grain weight. If more than 30 % of the root system is destroyed, severe yield losses must be expected (Asher and Shipton, 1981; Sieling, 1987; Sieling and Hanus, 1992).

Allelochemicals (fatty acids, phenolic acids) released during the decomposition of plant residues are known to cause yield reduction of cereals (McCalla and Norstadt, 1974; Müller-Wilmes et al., 1977; Wolf and Höflich, 1983; Siqueira et al., 1991; Christen and Lovett, 1993). The direct measurement is difficult and therefore several bioassays have been employed. Beside its use in the field of water purification, various *Lemna* species have gained broad acceptance for bioassays in ecological and allelopathy research, due to their easy handling as well as their sensitivity to a wide range of toxic substances. Duckweeds (*Lemna* spp.) are small floating angiosperms common to a wide range of rivers and lakes all over the world. The most common parameter in the detection of such phytotoxic activity has been the number of *Lemna* fronds after a period of growth, but also changes in individual dry weight, growth rate or chlorophyll content have been determined (Einhellig et al., 1985; Wink and Twardowski, 1992).

Different management strategies have been discussed to compensate for the yield losses due to unfavorable preceding crops. The effects of soil tillage (ploughing versus minimum tillage), different varieties and seed rate on the incidence of take-all and yield were often negligible (Sieling, 1987; Wallwork, 1989; Penrose, 1991; Olofsson, 1993). Delaying seeding date by 3–4 weeks prevented from a *G. graminis* infection in autumn and reduced take-all in the following growth period (Gilligan and Brassett, 1990; Sieling and Hanus, 1992). In order to increase ear density, the amount of N fertilizer, especially at the start of spring growth, showed positive results (Widdowson et al., 1985; Prew et al., 1986; Christen et al., 1992). However, most of the results available in the literature indicate that it is not possible to completely compensate for the detrimental influences of an unfavorable preceding crop on the grain yield of the subsequent wheat crop by optimizing crop management (Panse et al., 1994; Christen, 1998). Despite a large number of separate field experiments dealing with single factors, very little results about the interaction of various treatments are available.

The objectives of this paper were to quantify the effects of unfavorable preceding crop combinations on yield and yield components of wheat and to identify the stage when the single plant development started to differ. In addition, the occurrence of allelochemicals and take-all to cause these effects was tested. The possibility to compensate for the yield losses due to an unfavorable preceding crop by the different amounts and distributions of N fertilization was investigated.

2. Materials and methods

2.1. Site and soil

The experiment was carried out on a pseudo-gleyic sandy loam (Luvisol: 170 g kg^{-1} clay, pH 6.7, 9 mg kg^{-1} P, 15 mg kg^{-1} K, 13 g kg^{-1} C_{org},) at the Hohenschulen Experimental Farm (10.0°E, 54.3°N, 30 m a.s.l.) of the Kiel University, located in NW Germany 15 km west of Kiel (Schleswig-Holstein). Plant available K and P were determined by using the CAL method (Schüller, 1969).

The climate of NW Germany can be described as humid. Total rainfall averages 750 mm annually at the experimental site, with ca. 400 mm received during April–September, the main growing season, and ca. 350 mm during October–March (Table 1).

2.2. Treatments and design

The trial started in autumn 1989. In this paper, the results of the period 1993/1994–1998/1999 are presented. It was based on the rotation OSR–OSR–OSR–winter wheat–winter wheat–winter wheat, resulting in three different preceding crop combinations for the wheat: OSR–OSR (first wheat crop), OSR–wheat (second wheat crop), wheat–wheat (third wheat crop). In all years, the wheat variety 'Kraka' was grown. The OSR preceding the first wheat was treated uniformly to provide all wheat plots with similar starting condition.

Two sowing dates combined with different sowing rates were tested. The early sowing date was aimed at the second or third decade of September with 250–280 kernels m^{-2} seeded, the late one was performed about 3–4 weeks later with 320–350 kernels m^{-2} seeded. Under the climatic conditions of NW Germany, a delayed sowing date must be combined with increased seeding rates to compensated for the reduced plant development (tillering) before winter. Depending on the weather conditions, the exact dates differed between the years (Table 2). Ploughing and seed bed preparation was usually carried out 1 day before sowing.

Nitrogen (calcium ammonium nitrate with 27% N) was applied independently of the soil N content as a split-dressing at the beginning of spring growth (GS 25) (Zadoks et al., 1974), at the start of stem elongation (GS 30/31), and at ear emergence (GS 50/51). The N fertilization varied in amount (80–320 kg N ha^{-1}) and distribution (Table 3).

The field trial design was a split-split-plot design with two replications. Preceding crop combinations were main plots, sowing dates were sub-plots, and N fertilizer treatments were sub-sub-plots. In year 1 of the trial, each of the six crops of the rotation were grown separately on six main plots. Each main plot was then used for a complete rotation of the six crops with the rotation on any particular main plot beginning at the point in the rotation cycle corresponding to the initial main plot crop. Each crop was grown in each year and each main plot completed a complete rotation over the 6 years of the experiment.

Crop management not involving the treatments (e.g. application of herbicides, fungicides, insecticides and plant regulators) was conducted according to site-specific recommendations to achieve optimal yield.

The straw remained on the plots. The sub-sub-plot size was 12 m × 3 m, using an area of 3 m × 3 m for plant and soil sampling.

2.3. Plant sampling

Plants were sampled from 2 m × 0.5 m drilling rows in each plot on five dates ('Beginning of spring growth', GS 30/31, GS 50/51, GS 75, and GS 91). Total above ground dry matter, total number of plants (not at GS 75 and GS 91) and tillers were measured. At GS 91, number of ears and thousand grain weight were determined.

At GS 91, an area of 9 m^2 was combine-harvested and yield was adjusted to 14% water content based on the moisture content of a grain subsample. Except for 1994/1995, N offtake by the grain was obtained by multiplying yield with the N concentration of the seed determined by near-infrared (NIR) spectrometry. The number of kernels per ear was derived from the yield, the number of ears and the thousand grain weight.

At 'Beginning of spring growth', GS 30/31, GS 50/51, GS 75, and GS 91, roots of all wheat plants sampled to observe crop development were washed. The incidence of root rot, mainly caused by *G. graminis* var. *tritici*, was estimated on a scale from 1 (no visible symptoms) to 9 (root system totally destroyed).

To get more detailed information about the effects of the preceding crop on growth and development,

Table 1
Monthly rainfall (mm) and mean air temperature (°C) at Hohenschulen, Germany

	Mean air temperature (°C)							Total rainfall (mm)						
	1993/1994	1994/1995	1995/1996	1996/1997	1997/1998	1998/1999	30-year mean	1993/1994	1994/1995	1995/1996	1996/1997	1997/1998	1998/1999	30-year mean
September	11.9	13.2	13.5	12.1	13.5	13.8	13.4	103	116	82	49	55	48	66
October	7.9	8.0	11.8	9.5	8.2	9.0	9.6	60	63	22	58	68	159	60
November	1.7	7.1	3.9	4.7	4.1	2.4	5.4	28	6	22	97	25	74	76
December	3.1	4.1	−2.3	−0.6	2.9	1.3	2.4	156	122	17	37	58	63	74
January	3.6	1.0	−2.8	−1.6	3.5	3.2	0.7	82	134	5	3	95	74	62
February	−1.0	4.8	−2.8	4.3	5.2	1.2	0.7	31	85	21	88	15	53	45
March	4.6	3.5	0.4	4.9	5.0	5.0	3.0	115	69	8	51	50	77	46
April	8.2	7.2	7.9	6.3	8.0	8.2	6.7	33	35	15	27	95	27	49
May	11.8	11.1	9.8	10.8	12.7	12.0	11.3	59	63	52	88	35	48	51
June	14.1	14.0	14.0	15.4	15.1	14.2	15.2	54	62	26	71	85	62	62
July	20.5	18.6	15.4	17.7	15.2	18.1	16.4	66	16	37	123	109	78	77
August	17.4	18.8	18.1	20.7	15.7	16.8	16.3	117	30	35	56	61	83	86

Table 2
Sowing dates of winter wheat in the years 1993/1994–1998/1999 at Hohenschulen experimental station (NW Germany)

Year	Early sowing (SD1)	Late sowing (SD2)
1993/1994	13/09/1993	18/10/1993
1994/1995	22/09/1994	10/10/1994
1995/1996	19/09/1995	26/10/1995
1996/1997	16/09/1996	08/10/1996
1997/1998	19/09/1997	07/10/1997
1998/1999	26/09/1998	19/10/1998

10 plants per plot were collected each month throughout the growth period from selected plots and single plant dry matter was determined.

2.4. Lemna bioassay

In order to estimate the phytotoxic potential after different preceding crop combinations, a modified bioassay with *Lemna minor* was used according to the methods described by Einhellig et al. (1985). According to Cast et al. (1990), soil samples (30 g) were mixed with 60 ml of a 0.01 M EDTA buffer solution. The pH was adjusted to 7.0 using a 6N KOH solution. After shaking 2 h to ensure an optimal mixing, the soil suspension was centrifuged (4000 rpm at 20 °C) and filtered. 10 ml of the filtrate was narrowed down to 1 ml at 95 °C. 1 ml methanol (99%) was added to 1 ml of the filtrate to ensure sterile conditions.

Under a clean bench using aseptic techniques, 1.5 ml of the E medium (Cleland, 1979) was dispensed into each well of a sterile 24-well tissue culture plate using a sterile pipette. 5 μl of the filtrate were applied into each well of the tissue culture plate. *Lemna* colonies at the three-frond developmental stage were transferred by a flamed culture loop into each well. The culture plate was covered and placed in an environmental growth chamber at 28 °C under constant light (170 $\mu E\,m^{-2}\,s^{-1}$) using cool white light. In order to allow for better gas exchange as well as drying of evaporated culture medium, the lids of the culture plates were lifted every day for 5 min under the clean bench. After exactly 7 days, *L. minor* was carefully removed from each well of the culture plate and placed into water for a frond count.

2.5. Statistical analysis

Analyses of variance were done by using the SAS statistical package. Year was used as replication of main plots (preceding crop combination). $LSD_{0.05}$ for preceding crop combination is based on year × preceding crop combination interaction, that for sowing date is based on year × preceding crop combination × sowing date interaction effects, that for the mineral N treatments is based on residual effects. The $LSD_{0.05}$ applies only to individual treatment means.

To facilitate the comparison of 16 N treatments, a multiple regression approach was used and following model was fitted to the crop data:

$$Y = a + bN_T + cN_T^2 + dD1 + eD2 + fN_T D1 + gN_T D2 \qquad (1)$$

where Y is the grain yield (t ha^{-1}); N_T the total amount of nitrogen fertilization (kg N ha^{-1}); $D1$ is 0 and $D2$ is 0, if the preceding crop combination is 'OSR–OSR'; $D1$ is 1 and $D2$ is 0, if the preceding crop combination is 'OSR–wheat'; $D1$ is 0 and $D2$ is the 1, if the preceding crop combination is 'wheat–wheat'. *a*, *b*, *c*, *d*, *e*, *f* and *g* are constants, which were estimated using the REG procedure of SAS and are shown in Table 4.

Table 3
Amount and application time of the mineral N fertilizer (kg N ha^{-1})

	Time of application			Total amount
	Beginning of growth in spring	Beginning of stem elongation	Ear emergence	
N1	40	40	0	80
N2	40	40	80	160
N3	40	80	0	120
N4	40	80	80	200
N5	80	40	0	120
N6	80	40	80	200
N7	80	80	0	160
N8	80	80	80	240
N9	80	120	0	200
N10	80	120	80	280
N11	120	40	0	160
N12	120	40	80	240
N13	120	80	0	200
N14	120	80	80	280
N15	120	120	0	240
N16	120	120	80	320

Table 4
Estimates of parameters in Eq. (1) relating wheat grain yield (t ha^{-1}) of winter wheat to total N amount (kg N ha^{-1}) and the different preceding crop combinations

Parameter	Estimates	Standard error of the estimates	P-value
a: intercept	7.55	0.306	<0.0001
b: N_T	0.01981	0.003	<0.0001
c: N_T^2	−0.00004679	6.8×10^{-6}	<0.0001
d: $D1$	−1.95	0.252	<0.0001
e: $D2$	−3.03	0.252	<0.0001
f: N_TD1	0.00528	0.001	<0.0001
g: N_TD2	0.00566	0.001	<0.0001
RMSE	1.064		
R^2	0.41		<0.0001

N_T: total amount of nitrogen fertilization (kg N ha^{-1}); $D1$: 0 and $D2$: 0, if the preceding crop combination is 'OSR–OSR'; $D1$: 1 and $D2$: 0, if the preceding crop combination is 'OSR–wheat'; $D1$: 0 and $D2$: 1, if the preceding crop combination is 'wheat–wheat', RMSE: root mean squared error of model; R^2: multiple regression coefficient.

3. Results

3.1. Grain yield and yield components

Averaged over all treatments, wheat yield varied among years from 8.1 t ha^{-1} in 1998/1999 to 9.6 t ha^{-1} in 1996/1997 (Table 5). Due to the experimental design, no error estimate is possible for the effect of year and year by preceding crop combination interaction. The preceding crop combinations significantly influenced the yield of the subsequent wheat crop. The first wheat crop, grown directly after OSR, achieved on average nearly 9.5 t ha^{-1}, whereas the second wheat crop following wheat yielded about 0.9 t ha^{-1} and the third wheat crop following 2 years of wheat about 1.9 t ha^{-1} less compared with wheat after OSR. Delaying sowing date decreased grain yield by only 0.2 t ha^{-1}. It should be noted that, the first and the second wheat crop yielded more if early sown, while in the third wheat crop the effect of the sowing date was negligible.

Considering the average over all years, nitrogen fertilization increased grain yield after all preceding crop combinations, but at different levels (Fig. 1). Highest yields were observed in wheat after OSR with a maximum of 9.7 t ha^{-1} with 210 kg N ha^{-1}. The third wheat crop showed the lowest yield over the whole range of tested N amounts. To achieve the yield maximum of 8.0 t ha^{-1}, a N amount of 270 kg N ha^{-1} was necessary. Yield differences due to the preceding crop combination were larger at low levels of N fertilization. The wheat crop following OSR–wheat ranged between both curves. However, the effect of the nitrogen fertilization on grain yield was significantly less pronounced with OSR–OSR than with the other preceding crop combinations. Large year by year variation caused a relative low R^2 value of 0.41.

Averaged over all 6 years, the yield maximum of wheat following OSR was 0.7 and 1.7 t ha^{-1} higher

Table 5
Effect of year, sowing date and preceding crop combination on wheat yield (t ha^{-1}) (1993/1994–1998/1999, n = 1152)

Year	Preceding crop combination			Mean
	OSR–OSR	OSR–wheat	Wheat–wheat	
1993/1994	9.97 (100)[a]	8.07 (81)	6.78 (68)	8.27
1994/1995	8.88 (100)	9.22 (104)	6.62 (74)	8.24
1995/1996	9.03 (100)	8.22 (91)	7.44 (82)	8.23
1996/1997	10.09 (100)	9.84 (98)	8.76 (86)	9.57
1997/1998	9.09 (100)	8.65 (95)	8.55 (94)	8.76
1998/1999	9.67 (100)	7.52 (78)	7.13 (74)	8.11
Sowing date				
Early sowing (SD1)	9.57 (100)	8.72 (91)	7.54 (79)	8.61
Late sowing (SD2)	9.34 (100)	8.45 (90)	7.55 (81)	8.45
Mean	9.45 (100)	8.59 (91)	7.55 (80)	

$LSD_{0.05}$ for the preceding crop combination = 1.47; $LSD_{0.05}$ for the sowing date = n.s.; $LSD_{0.05}$ for the sowing date × preceding crop interaction = n.s.; No error estimate is possible for the effect of the year and the year × preceding crop combination.
[a] Relative wheat yield; yield of wheat following OSR–OSR = 100.

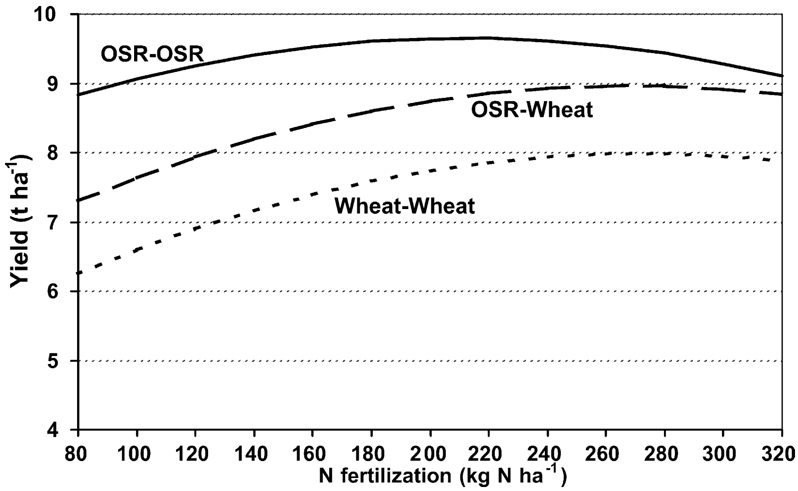

Fig. 1. Effect of N fertilization on yield of winter wheat (t ha^{-1}) following different preceding crop combinations (OSR–oilseed rape) (1993/1994–1998/1999) ($R^2 = 0.41^{***}$, $n = 1152$). Estimates of the parameters are shown in Table 4.

than that of wheat after wheat and of the third wheat crop, respectively (Table 6). The range was the same in 5 out of 6 years, only in 1995/1996, the second wheat crop outyielded the wheat after OSR because of difficulties in the plant establishment in the first wheat crop.

As presented in Table 5, the yield losses showed a large year to year variation. In a first approach, we related the yield losses due to an unfavorable preceding crop combination to the accumulated water balance (rainfall minus transpiration from May to July) of the corresponding year (Fig. 2). Increasing water availability in these period significantly decreased yield losses in the third wheat. In the second wheat, a similar trend was observed, which was, however, not significant at $P = 0.05$.

The effects of the single N splittings on grain yield depended on the preceding crop combinations. After

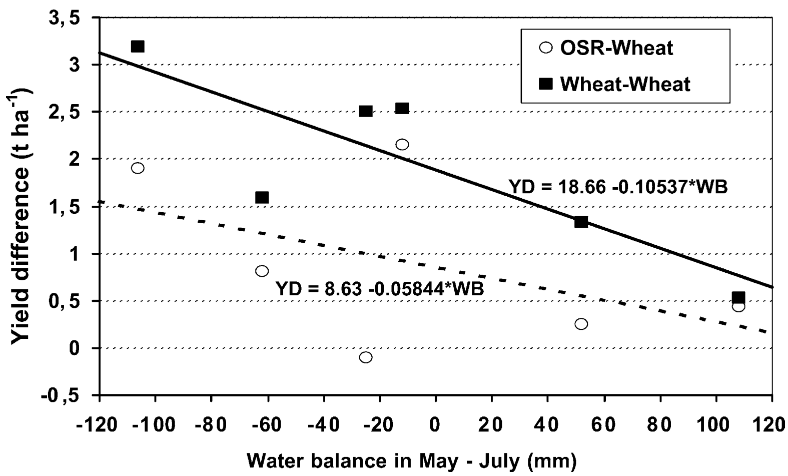

Fig. 2. Effect of the water balance (WB) from May to July (mm) on the yield losses (YD) (t ha^{-1}) in wheat following oilseed rape (OSR)–wheat (dotted line, $R^2 = 0.24$ (ns), $n = 6$) and wheat–wheat (solid line, $R^2 = 0.71^{*}$, $n = 6$) compared with wheat following OSR (1993/1994–1998/1999).

Table 6
N fertilization (kg N ha^{-1}) for yield maximum (t ha^{-1}) of wheat following different preceding crop combinations in 1993/1994–1998/1999

Preceding crop combination	N1	N2	N3	N_{total}	Yield maximum (t ha^{-1})
1993/1994					
OSR–OSR	40	90	80	210	10.63
OSR–wheat	120	115	80	315	9.15
Wheat–wheat	120	120	80	320	8.59
1994/1995					
OSR–OSR	80	120	80	280	9.44
OSR–wheat	75	120	80	275	10.01
Wheat–wheat	120	90	0	210	7.03
1995/1996					
OSR–OSR	0	120	80	200	10.25
OSR–wheat	0	120	80	200	9.02
Wheat–wheat	0	120	80	200	8.41
1996/1997					
OSR–OSR	0	100	80	180	11.52
OSR–wheat	105	25	80	210	10.62
Wheat–wheat	105	45	80	230	9.56
1997/1998					
OSR–OSR	120	0	80	200	10.67
OSR–wheat	120	0	80	200	9.94
Wheat–wheat	120	15	80	215	9.62
1998/1999					
OSR–OSR	0	120	80	200	10.90
OSR–wheat	60	120	80	260	8.05
Wheat–wheat	120	0	80	200	7.94
All years					
OSR–OSR	0	115	80	195	10.54
OSR–wheat	25	120	80	205	9.22
Wheat–wheat	120	70	80	270	8.24

Table 7
Effect of N application at the beginning of growth in spring (N1), and stem elongation (N2) (kg N ha^{-1}) and preceding crop combination on wheat yield (t ha^{-1}) (1993/1994–1998/1999, n = 1152)

N fertilization		Preceding crop combination		
N1	N2	OSR–OSR	OSR–wheat	Wheat–wheat
40	40	9.36	7.56	6.66
40	80	9.63	8.67	7.44
80	40	9.61	8.45	7.41
80	80	9.64	8.68	7.56
80	120	9.45	8.90	7.84
120	40	9.41	8.66	7.72
120	80	9.32	9.04	7.99
120	120	9.21	8.73	7.76

$LSD_{0.05}$ for N1 × N2 × preceding crop interaction = 0.24.

OSR, an increase of the N application at the beginning of growth in spring or that at stem elongation up to 80 kg N ha^{-1} increased grain yield, whereas 120 kg N ha^{-1} decreased it (Table 7). In contrast, the second and the third wheat crops, both realized the highest yields in the 120/80 kg N ha^{-1} (N1/N2) treatment. Applying 120 kg N ha^{-1} at both dates decreased grain yield. An application of 80 kg N ha^{-1} at ear emergence increased grain yield in all wheat crops significantly, mainly due to a higher thousand grain weight (data not shown).

Averaged over all N treatments, the preceding crop did not affect the grain N concentration (data not shown). However, the interaction between the N application at ear emergence (N3) and the preceding crop combination revealed that the increase in the grain N concentration due to the N3 splitting was highest in the third wheat crop compared with wheat after OSR (Table 8). Total N uptake by the grain was mainly

Table 8
Effect of N application at ear emergence (N3) (kg N ha^{-1}) and preceding crop combination on grain N concentration (g kg^{-1}) (1993/1994–1998/1999, except 1994/1995[a]; n = 960)

N fertilization (N3)	Preceding crop combination			Mean	$LSD_{0.05}$
	OSR–OSR	OSR–wheat	Wheat–wheat		
0	19.9	18.6	18.6	19.0	
80	22.9	23.3	24.0	23.4	0.2
Mean	21.4	20.9	21.3		
$LSD_{0.05}$		n.s.			

$LSD_{0.05}$ for N3 × preceding crop interaction = 0.5.
[a] In 1994/1995, grain N concentration has not been determined.

Table 9
Effect of N application at the beginning of growth in spring (N1), N application at stem elongation (N2) (kg N ha^{-1}) and preceding crop combination on number of ears m^{-2}, derived number of kernels per ear and thousand grain weight (g) (1993/1994–1998/1999, $n = 1152$)

N fertilization		Number of ears m^{-2}			Number of kernels per ear			Thousand grain weight (g)		
N1	N2	OSR–OSR	OSR–wheat	Wheat–wheat	OSR–OSR	OSR–wheat	Wheat–wheat	OSR–OSR	OSR–wheat	Wheat–wheat
40	40	498	426	397	43.4	40.9	44.1	45.2	44.7	39.8
40	80	517	462	431	43.6	44.2	45.0	44.4	44.6	40.2
80	40	498	472	429	44.5	41.6	45.6	44.7	44.2	40.0
80	80	523	515	434	44.1	41.6	46.6	43.3	42.8	39.3
80	120	520	504	470	43.7	43.2	43.2	43.0	42.3	39.8
120	40	503	510	447	44.3	40.8	44.3	44.3	43.1	41.0
120	80	522	522	449	43.4	42.1	45.8	43.0	42.3	40.4
120	120	527	528	483	42.6	42.5	42.4	42.6	41.3	39.4
Mean	514 (100)	492 (96)	443 (86)	43.7 (100)	42.1 (96)	44.6 (102)	43.8 (100)	43.2 (98)	40.0 (91)	
$LSD_{0.05}$		43			n.s.			3.1		

controlled by the yield (data not shown). Since the wheat following two wheat crops realized the lowest yields, N uptake by the grain was also low, despite the increased grain N concentration (data not shown).

Averaged over all years and factors, an unfavorable preceding crop combination significantly decreased number of ears m^{-2} and thousand grain weight, being very pronounced in wheat following wheat–wheat, whereas thousand grain weight in the second wheat crop was only slightly affected (Table 9). In contrast, number of kernels per ear partly compensated for the reduction of the other yield components.

The positive effects of nitrogen fertilization at the beginning of growth in spring (N1) and at stem elongation (N2) on the yield of wheat following wheat was mainly based on an increase in the ear density (Table 9). Neither the kernel number per ear nor the thousand grain weight were affected by the N supply.

3.2. Single plant development

The different preceding crop combinations caused non-significant differences in the single plant biomass at the first plant sampling at the end of October, 4 weeks after plant establishment (Table 10). Wheat plants following OSR accumulated more biomass than plants following a wheat crop. Plants of the third wheat crop were the smallest. This ranging persisted at all sampling dates, however, due to large year to year variation, only the differences at the sampling in May and June were statistically significant ($P < 0.05$).

3.3. Tiller density and plant biomass during the growing season

During spring and early summer, the number of tillers m^{-2} increased until starting of shooting at GS 30/31 (Table 11). Tiller density ranked in the same way at all sampling dates. Directly after winter, wheat plants following OSR showed the best development and with 930 tillers m^{-2} the highest tiller number, whereas wheat plants grown after wheat produced clearly less tillers with 800 and 740 tillers m^{-2}, respectively.

The total aboveground biomass showed a similar response to cropping history (Table 11). Again, at all sampling dates, the highest biomass occurred in wheat grown after OSR, while lowest values were observed in the third wheat. Since the preceding crop combination did not adversely affect the number of plants m^{-2} (data not shown), the number of tillers per plant and the biomass per plant, characterizing the development of the single plant, was affected.

3.4. Root rot incidence

Prior to tiller counting and biomass weighting, the plant roots were examined for root rot on a scale ranging from 1 (no visible symptoms) to 9 (root system totally damaged). In general the incidence was very small at all sampling dates, however, wheat after OSR was significantly less infected than wheat following two wheat crops (Table 11).

3.5. Lemna bioassay

A reduced number of fronds indicated the presence of allelochemicals. Although in most cases not statistically significant, at all sampling dates until December a similar range of the preceding crop combinations following the order OSR–OSR > OSR–wheat > wheat–wheat was observed (Table 12). In contrast, the soil extracts from the spring samples showed no trend.

Table 10
Effect of preceding crop combination on single plant biomass (g) throughout the growing season (1993/1994–1996/1997, early sowing date, $n = 192$ per sampling date)

Sampling date	Preceding crop combination			$LSD_{0.05}$
	OSR–OSR	OSR–wheat	Wheat–wheat	
End of October	0.045	0.038	0.036	n.s.
End of November	0.108	0.077	0.065	n.s.
Mid of January	0.177	0.122	0.109	n.s.
Mid of April	0.322	0.297	0.252	n.s.
Mid of May	1.58	1.32	1.15	0.40
Mid of June	4.68	3.58	3.69	0.63

Table 11
Effect of preceding crop combination on number of tillers m^{-2}, total above ground biomass ($g\,m^{-2}$) and incidence of root rot (1–9) at different growth stages (1993/1994–1996/1997; $n = 768$ per sampling date)

Preceding crop combination	Sampling date				
	Beginning of growth in spring	GS 30/31	GS 50/51	GS 75	GS 91[a]
Tillers m^{-2}					
OSR–OSR	928	1066	686	575	516
OSR–wheat	796	996	684	540	507
Wheat–wheat	737	931	522	507	458
$LSD_{0.05}$	151	n.s.	n.s.	44	51
Total biomass ($g\,m^{-2}$)					
OSR–OSR	44.3	229.9	1109.5	1950.9	1914.0
OSR–wheat	40.4	198.3	1030.7	1749.4	1651.5
Wheat–wheat	35.0	178.3	906.8	1566.4	1578.8
$LSD_{0.05}$	n.s.	n.s.	196	309	208
Root rot rating (1–9)					
OSR–OSR	1.1	1.2	1.2	1.3	1.2
OSR–wheat	1.3	1.4	1.7	1.8	1.6
Wheat–wheat	1.4	1.6	1.9	2.1	2.0
$LSD_{0.05}$	0.3	0.3	0.7	0.7	n.s.

[a] Root rot rating only in 1994/1995–1996/1997, $n = 576$.

Table 12
Effect of preceding crop combination on mean number of fronds in the *Lemna* bioassay (1993/1994–1996/1997; $n = 84$)

Sampling date	Preceding crop combination			$LSD_{0.05}$
	OSR–OSR	OSR–wheat	Wheat–wheat	
Third decade of October	31.3	30.2	29.3	n.s.
First decade of November	30.5	28.3	27.8	n.s.
Second decade of November	29.1	29.7	26.8	n.s.
Third decade of November	31.8	29.1	26.4	3.23
First decade of December	29.2	27.1	25.9	n.s.
Third decade of April	35.7	34.2	34.4	n.s.
First decade of May	30.6	31.7	31.4	n.s.
Third decade of May	34.0	32.4	35.5	n.s.

Neither the nitrogen fertilization to the preceding nor to the growing crop affected the growth of *Lemna*.

4. Discussion

The main objective of this paper was to quantify the yield losses of wheat following unfavorable preceding crop combinations. Averaged over all years and all factors, wheat following OSR realized a higher grain yield compared with wheat following wheat (Table 5), a fact, which is corresponding well with results from other experiments (e.g. Zimmermann, 1984; Widdowson et al., 1985; Prew et al., 1986; McEwen et al., 1989; Christen, 1998). The yield of the third wheat crop, following wheat–wheat, achieved the lowest yield, being 20% less than that of the first wheat crop. Other researchers also reported of dramatic yield decreases by 30–40% in the first 3–4 years of a wheat monoculture and an increase in the following years, known as ‘decline-effect’ in the larger sense (Gerlagh, 1968; Shipton, 1975; Sieling and Hanus, 1990).

The yield losses due to an unfavorable preceding crop combination was mainly due to a reduced number of ears m^{-2} and a decreased thousand grain weight (Table 9, Christen, 1998), suggesting at least two different causes and/or dates of the occurrence. The plant establishment and therefore the number of plants m^{-2} was not affected. However, at the end of October, about 4 weeks after sowing, wheat plants following the different preceding crop combinations varied in plant biomass (Thorne et al., 1988; Theuer, 1997).

The design of this field trial consisting of six fields was a split-plot with two levels of splitting and the preceding crop combinations (=one field) as main factor. From the practical point of view, it was an advantage because each field could be managed separately. But the design complicated the statistical analysis, only allowing to test the effects of the preceding crop combinations against the interaction between year and preceding crop combinations, which resulted in relative large values for the least significant difference. However, the investigations were made over a period of 4 and 6 years for plant biomass and the yield, respectively. In addition, repeated and independent measurements within the growing period revealed a similar tendency. Different sowing dates and their interaction with the preceding crop combination only slightly affected the observed parameters and were neglected.

From the possible causes of yield response to different preceding crops, the occurrence of weeds as well as the soil analysis for phosphorus (P) and potassium (K) revealed no relation to the preceding crop combinations (Winkelmann, 1999). Based on the investigations in 1 year, significant changes in parameters concerning the soil physics could not be observed within the first 3 years of a wheat monoculture (Menzel, personal communication). Since the incidence of root rot, caused by *G. graminis*, was very low (Table 11), we argued that this disease did not negatively affect the plant growth at this site. Therefore, a delay in the sowing date in order to prevent root rot infections in autumn seems not promising in our experiment.

The *Lemna* bioassay (Table 12) showed a large variation from date to date as well as from year to year, presumably due to differences in the conditions during the stock-culture periods (Christen and Theuer, 1996). In addition, the weather conditions and in consequence the decay of the plant residues as well as the decomposition of the allelochemicals varied with the years. However, although not significant, the *Lemna* bioassay indicated a higher level of phytotoxic substances in the soil after wheat in autumn. The N applied to the preceding crop had no effect (data not shown). In pot experiments under controlled conditions, allelochemicals such as phenols or fatty acids originated from the decomposition of plant residues as straw and stubbles reduced grain yield (Christen and Lovett, 1993). Although a transfer of these results from the green house into field conditions with higher microbiological activity is difficult, the possibility of allelochemical effects must be taken into account. In spring, no trend could be observed, presumably because the substances had decomposed in the meantime.

As another potential cause for the different growth of wheat following wheat compared with wheat after OSR, the supply with nitrogen in autumn must be considered. Christen (1990) observed small differences in the amount of mineral N in the first 30 cm of the soil in autumn. OSR returned large amounts of easily mineralizable crop residue (petals and leaves, residues) to the soil after flowering and at harvest and left the soil in a favorable structure. Consequently, the mineralization potential and the soil mineral N after OSR were supposed to be higher than after wheat. In addition, more important than the average N content of a 30 cm layer is the N supply in the rooting zone, being only 5–10 cm in the first weeks after germination. Given a sufficient soil-N supply, it could be argued that the wheat plants following wheat might take up N at lower rates because of a smaller root system, presumably due to the allelochemicals. The assumption of a N effect is supported by the results of other experiments where an additional autumn N fertilization applied as slurry to wheat following OSR resulted in a better single plant development in 3 out of 6 years (Sieling, 2000), allowing a better transformation of the growing factors (radiation, N) into yield. Since the early development of the single plant and its root system seems to be very important for the later growth, further investigations are needed to identify the mechanisms occurring after the different preceding crop combinations.

During the growth from spring until harvest, the differences in the single plant development due to the preceding crop combinations remained in the same order (Table 11). In addition, grain filling was less in wheat following wheat, resulting in a lower thousand grain weight. Due to a smaller root system, the plants were more susceptible to stress throughout the growing season (Schönhammer and Fischbeck, 1987) and therefore not able to compensate for the lower tiller density. The role of the root system (size and/or efficiency) for the explanation of the described differences in growth, development and yield is supported by another hypothesis. As shown in Fig. 2, yield losses due to an unfavorable preceding crop (combination) increased with increasing drought stress. This fact indicates that the ability of the root system to take up water and nutrients was reduced.

In spring, the N fertilization varied from 80 up to 320 kg N ha^{-1}, therefore maximum rates exceeded the N requirement in any case. However, even a N supply exceeding the N requirement only partly decreased the yield losses due to an unfavorable preceding crop (combination) (Widdowson et al., 1985; Prew et al., 1986; Panse et al., 1994). Our results indicated that both, the first N application at the beginning of growth in spring and also the second N application at stem elongation, should be increased in order to reduce yield losses in wheat following wheat due to a lower ear density. On the other hand, both applications might be reduced in a wheat following a favorable preceding crop.

Without N fertilization at ear emergence, an unfavorable preceding crop reduced grain N concentration (Table 8). Applying 80 kg N ha^{-1} increased grain N concentration in wheat after wheat more than in wheat after OSR, mainly due to the higher yield level of the first wheat crop and the corresponding dilution effect.

From an ecological point of view, a favorable preceding crop should be preferred, since the N uptake by the grain was mainly affected by yield, despite the slightly higher grain N concentration in the wheat after wheat. Lower N uptake in combination with the higher N fertilization (Table 6) resulted in larger N residues remaining in the soil after harvest, which may increase the N leaching potential in the long-term (Sieling, 2000). However, after calculations of Christen (1998), wheat monoculture was one of the most economical rotations, although rotations including OSR, peas and/or oats showed higher grain yields. Future investigations on the nitrogen efficiency should be extended to whole crop rotations and/or farming systems.

Acknowledgements

The Ph.D. projects of Christiane Stahl (born: Theuer) and Christoph Winkelmann were funded by the Deutsche Forschungsgemeinschaft.

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